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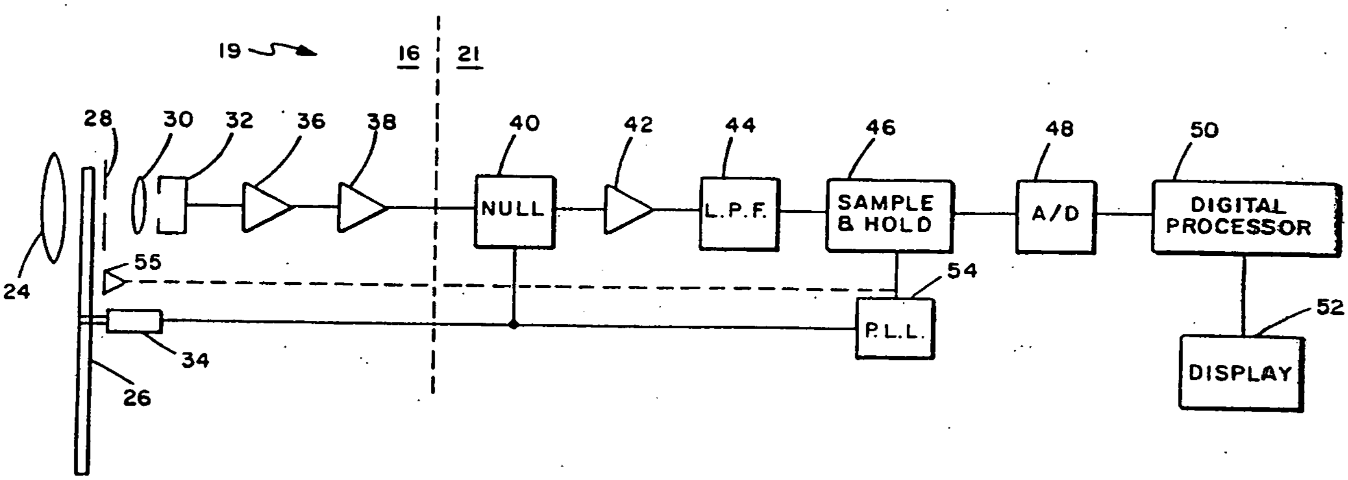

(57) Abstract

The invention relates to the remote infrared radiometric detection of chemical vapors (20). Air quality and substance control concerns present a need for more efficient ways of detecting the presence of select chemical vapors (20) in the atmosphere. A method and apparatus for such a detector includes elements for filtering (26, 34) collected infrared energy over a filter bandwidth by bandpass filtering only a fractional bandwidth of the filter bandwidth at any one time and repeatedly scanning the filter bandwidth with the passed fractional bandwidth. Also included are elements for measuring infrared energy (32) passed by the bandpass filtering thereby producing an output signal and for repeatedly nulling (40) the output signal in relation to the repeated scanning of the filter bandwidth. The invention is applicable to air monitoring including pollution control, chemical detection and the detection of any substances which provide telltale chemical vapors (20).

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INFRARED CHEMICAL VAPOR DETECTOR AND METHOD

Background of the Invention

Field of the Invention

The present invention generally relates to the identification of chemical vapors by means of infrared (IR) radiation emission and absorption and particularly to the performance of such detection at a location remote from the vapors detected.

Statement of the Prior Art

Increasing concern for various aspects of our environmental quality has generated a need in our technical capability for the convenient and remote detection of various substances which might take the form of vapors present in air. Various existing systems range in nature from laser photoacoustic detection to differential absorption Lidar, to fluorescence or luminescence spectroscopy, and to thermal infrared emission imaging. Unfortunately, all of these methods are very expensive high-technology systems requiring complex operation and extensive signal processing. All, except thermal imaging, require active illumination which beacon their presence. These factors tend to enforce substantial limits on the nature and frequency of the use of the respective methods. Understandably, there is, therefore, a need for such detection equipment and

methods which are less expensive, easier to operate and simpler in nature to provide faster detection results.

SUMMARY OF THE INVENTION

In one form, the present invention provides an infrared radiometer, comprising means for collecting infrared energy, means for filtering the collected energy over a filter bandwidth including filter means for bandpassing only a fractional bandwidth of the filter bandwidth at any one time and means for repeatedly scanning the filter bandwidth with the passed fractional bandwidth, means for measuring infrared energy passed by the filter means and for producing an output signal in response thereto, and means for repeatedly nulling the output signal in relation to the repeated scanning of the filter bandwidth.

In another form, the present invention provides an apparatus for detecting the presence of substance vapors having known infrared spectral characteristics against a background having contrasting infrared spectral characteristics relative to the known infrared characteristics of the substance vapors, comprising means for collecting infrared energy emissions from the background and any vapors present between the background and the means for collecting, means for measuring the infrared energy levels collected both in a first plurality of wavelength bands known to contain

infrared characteristics of the substance vapors and in a second plurality of wavelength bands known to contain infrared characteristics of the background, and means for comparing the infrared energy levels measured in the first and second plurality of bands for determining the presence of substance vapors based upon the relative infrared energy levels measured in the first and second plurality of bands.

In one form, the method of the present invention provides for collecting infrared energy, filtering the collected energy over a filter bandwidth including bandpass filtering only a fractional bandwidth of the filter bandwidth at any one time and repeatedly scanning the filter bandwidth with the passed fractional bandwidth, measuring infrared energy passed by the bandpass filtering producing an output signal in response thereto, and repeatedly nulling the output signal in relation to the repeated scanning of the filter bandwidth.

In another form, the present invention covers a method for detecting the presence of substance vapors having known infrared spectral characteristics against a background having contrasting infrared spectral characteristics relative to the known infrared characteristics of the substance vapors, comprising the steps of collecting infrared energy emissions from the background and any vapors present against the

background, measuring the infrared energy levels collected both in a first plurality of wavelength bands known to contain characteristics of the substance vapors and in a second plurality of wavelength bands known to contain characteristics of the background, and comparing the infrared energy levels measured in the first and second plurality of bands for determining the presence of substance vapors based upon the relative infrared energy levels measured in the first and second plurality of bands.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustratively described in reference to the accompanying drawings in which:

Fig. 1 is a representational diagram of a remote detection environment in which the present invention is intended to operate;

Fig. 2 is a schematic block diagram of a vapor detection apparatus constructed in accordance with one embodiment of the present invention;

Fig. 3 is an infrared spectral diagram of an infrared filter designed to function in accordance with the embodiment of Fig. 2; and

Fig. 4 is a flow chart of signal processing performed by the apparatus of Fig. 2.

DETAILED DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a typical infrared (IR) detection environment 10 in which the apparatus and method of the present invention are intended to operate. The environment 10 generally includes a background 14 having measurable infrared emission/absorption/ reflection characteristics, and a non-imaging infrared detector 16. Detector 16 is aimed in the direction of arrow 18 toward the background 14 to detect for the possible presence of selectable chemical vapors 20 as may pass in the area 12 between the background 14 and the detector 16. Area 12 may also include normal atmospheric air 12 capable of sustaining human and other forms of life. More specifically, the background 14 is selected so that it has a different temperature from the vapors being detected. This contrast may alternatively include the detection of warm vapors against a cool background or the detection of cool vapors against a warm background. The contrast provides the basis for a detectable infrared difference. The background 14 either may be man-made such as a surface or wall, or may be opportunistically selected such as a hillside or sky. Background 14 does not have to have a stable temperature, so long as its temperature generally contrasts that of vapors 20.

Fig. 2 shows a schematic block diagram of an apparatus 19 constructed in accordance with one

embodiment of the present invention and capable of performing the detection of selectable chemical vapors such as 20 in the environment 10 of Fig. 1. Apparatus 19 generally includes the detector 16 of Fig. 1 and a processor section 21.

The detector 16 is directed so that infrared energy emanating from the background 14 traverses through the chemical vapors 20 and is collected by the aperture of an objective lens 24. The chemical vapors 20 selectively absorb or radiate IR energy in accordance with their own unique IR characteristics and in response to the relative differential temperature between the background 14, the vapors 20 and any air or gasses present in the testing environment. The IR energy collected by the objective lens 24 passes through a rotating, continuously varying infrared spectral bandpass filter 26, a slit 28 and a field lens 30. The field lens 30 collects the energy onto an IR detector 32. The filter 26 is rotated at a fixed rate with motor 34 and causes the detector 32 to see repeated scans of infrared wavelengths. In other words, the functioning of the apparatus described thus far produces an IR spectral radiometer.

This IR spectral radiometer may be constructed to cover any partial bandwidth of the IR spectrum which is of interest. This design aspect depends primarily upon the rotating filter 26.

Filter 26 is circular and allows the passage therethrough of a continuously varying wavelength of IR energy. The wavelength varies in accordance with the rotational angle of the filter over a predetermined filter bandwidth. In one embodiment, the wavelength varies continuously from (6) to (11.4) microns, both increasing and decreasing the passed wavelength so that the (6) to (11.4) micron filter bandwidth is scanned a total of four (4) times in one rotation of the filter. Each scan of the bandwidth may also be thought of as a frame.

The IR energy passed at any point around the filter is only a fractional bandwidth of the overall filter bandwidth. In the above example, this fractional bandwidth is (0.2) microns.

By selection of the filter 26, the filter bandwidth of a detector may be tailored so that the detection apparatus may be dedicated for the long term monitoring of either a single vapor or a group of vapors having sufficiently proximate IR characteristics.

The IR energy level that impinges on the detector 32 is detected or measured causing the detector 32 to produce an output signal which is amplified by a preamplifier 36 and an amplifier 38. The amplified output signal from amplifier 38 is then coupled to the processor section 21 which may be

constructed either integral with or separate from detector 16.

The output signal from amplifier 38, which corresponds to the IR energy detected is then chopped or nulled by a null circuit 40. Null circuit 40 causes the signal from amplifier 38 to be shorted to ground between each bandwidth scan of filter 26. This prevents scan to scan propagation of 1/f noise by producing a deep signal null between successive scans. In the example described above, where the filter bandwidth is scanned a total of four times during each rotation of the filter 26, it is possible to use one or more of the filter bandwidth scans produced per rotation and to null the signal during the unused scans or between adjacent scans. It may also be said that the output signal is nulled at the same rate that the filter bandwidth is scanned. Nulling the signal just prior to the scan enables a stable starting point for the output signal, and nulling the signal after the end of the scan reduces the unpredictable response caused by 1/f noise. Synchronization of this nulling is described below.

This reduction of 1/f noise enables improved performance for the entire detection apparatus. Where conventional approaches might use a lower scan rate and a separate high frequency modulator to limit the 1/f noise effect, this variation of the present invention

allows a higher scan rate, providing more data for more accurate signal processing.

The resultant signal out of null circuit 40 is buffered by a buffer amplifier 42 and filtered by a low pass filter 44. The filtered analog signal is sampled by a sample and hold circuit 46 and converted to a digital format by an analog to digital (A/D) converter 48. A digital signal processor 50 processes the digitally formatted data using an algorithm described below and outputs the results to a display 52.

The sample and hold circuit 46 and null circuit 40 are synchronized to the circular filter 26 by means of a phase-locked loop 54. This synchronization enables effective nulling and identification, for processing purposes of the filter position and therefore the IR wavelength of each sample taken. Any other suitable means may alternatively be used for synchronizing the nulling and/or the sampling to the wavelength position of filter 26. An example, in the form of a reflecting detector 55, is optionally shown. Such a detector may be made to respond either directly to the filter or otherwise to the motor 24 drive shaft.

The analog data is over sampled, by sample and hold circuit 46, at a rate which is nominally ten times the rate of change of filter 26. In the example given, the filter bandwidth extends from (6.0) to (11.4) microns for a total of (5.4) microns, and the

fractional bandwidth passed by filter 26 at any point in time is (0.2) microns. The sampling is controlled to produce a sample every (0.02) micron of wavelength change and therefore produces a total of (270) samples per scan of the bandwidth. It is these (270) samples produced by every scan of the bandwidth that are digitized and used by the processor 50.

The system thus far described repeatedly scans the IR spectrum of interest to enable detection of differences in the measured IR energy at selected wavelengths, caused by the presence of various substance vapors contrasted against the background. This detection of differences is performed with the signal processing described below.

Processor 50 processes the digitized samples in accordance with the flow chart 60 of Fig. 3. Generally, Filter Calculation step 62 uses the samples to calculate (54) separate filter values evenly spaced across the scanned filter bandwidth. These filter values are taken by the Filter Correction step 64 and individually corrected for the transfer function of the detector 16. The adjusted filter values are then adjusted by subtraction of an estimated background temperature by the Background Subtraction step 66. With the background temperature subtracted, the filter values are then integrated for a multiplicity of filter bandwidth scans by Integration step 68 for the purpose

of removing noise. Once data for a sufficient number of scans is accumulated, the integrated filter values are then tested for the known IR spectral characteristics of the compounds of interest by Detection step 70. The individual steps of flow chart 60 are discussed below in greater detail.

For each rotation of filter 26, Filter Calculation step 62 takes the (270) samples and forms (54) overlapping spectral bandpass filters that are the average of ten samples and are separated by five samples. The oversampling rate of 10 is nominal, and generally the number of samples may be any suitable multiple of the filter bandwidth (5.4) divided by the fractional pass bandwidth (0.2) for purposes of computational ease. Fig. 4 shows an example of sample grouping which may be used to calculate a set of narrow band filter values. Each of the points in the left hand column represents a sample value from A/D converter 48. Each of the actual wavelength values appearing in the right hand column represents the center wavelength of a narrow band filter value. The wavelength of each of the samples in the left hand column may be read or interpolated from the values appearing in the right hand column.

Each of the narrow band filter values is calculated by summing (or averaging) the ten (10) nearest sample values. This means that the (6.1)

micron filter value is calculated by summing the values for samples (6.0) through (6.2); the (6.2) filter value is summed from samples (6.1) through (6.3); and so on.

This method produces (54) narrow band filter values over the bandwidth of filter 26. Each narrow band filter is (0.2) microns wide, which corresponds to the bandpass characteristics of filter 26, and each narrow band filter is separated from adjacent filters by (0.1) microns. Because of this relationship, the samples included in the computation of each filter value represent potential infrared energy passed by the filter with the wavelength of the respective filter value.

The Filter Correction step 62 next corrects each calculated filter value for the system transfer function at each wavelength by multiplying each filter value by a unique coefficient determined by system calibration.

The Background Subtraction step 66 next uses the filter values to calculate the level of an estimated or equivalent background temperature across the filter bandwidth and subtracts the calculated temperature level from each of the filter values. The background temperature may be calculated by any suitable method. In one method, "clear" filter values are determined either by just looking at wavelengths not affected by the compound of interest or by otherwise examining the

filter values. From these "clear" filter values, a temperature value for all filters is estimated by minimizing a mean square error criteria to find an equivalent blackbody temperature which best fits the measured values in the "clear" filters. The estimated temperature value in all filters is subtracted from the measured signal in all filters to normalize the data.

This normalization, including estimation, is performed every frame or scan of the filter bandwidth and is the basis for detecting the substance vapors 20 against the contrasting background 14. The equivalent blackbody temperature, which is determined, is the background temperature against which the vapors 20 are contrasted. In the instance where cold vapors are detected against a warm background, subtracting the background temperature results in a negative number at the wavelengths of interest. Other negative numbers are also generated due to noise in the measurements. The resulting values, both negative and positive, are then used by the Integration step 68.

The Integration step 68 accumulates data for successive frames or full filter bandwidth scans. This may be done for either a fixed number of scans or in response to one or more accumulated filter values. Noise signals in the measurements are eliminated by this integration or accumulation. If there is an IR signal, other than noise, present at any wavelength

within the scan bandwidth, the signal will integrate to its final value.

The integrated residual filter values are then passed to Detection step 70. Detection of compounds of interest may be accomplished by any suitable means. In one means, a microprocessor may be used to logically and mathematically examine the filter values, comparing them against known "footprints" or IR spectral characteristics of the compound of interest. This approach affords programmability of the system for the detection of one or more of a variety of substances thereby reducing adaptation costs for each different application. This programmability even extends to substance concentration and temperature. In an alternative detection approach, a neural network device/processor can be used to make the classification/detection decision. Such an approach would be used for detecting a large variety of substances.

Again this detection process is intended to find differences between the IR energy measured at wavelengths having known spectral characteristics for the substances of interest. These detected differences may be either positive or negative depending upon the relative temperature differences between the background and the vapors to be detected.

After detection, any desirable information may be passed to the display 52. This might include the substance name, concentration, temperature, etc. or something as simple as an indicator signal that a specific substance is present or has exceeded a specific concentration level. This data can also be transmitted for distant monitoring, collection, analysis, etc.

CONCLUSION

The present invention provides a unique apparatus and method which is readily adaptable for the detection of a wide variety of substances in gaseous form. The present invention may be applied to any situation in which a contrasting IR background is available and against which a gaseous volume may be monitored. The invention thereby provides remote monitoring which affords an extremely wide range of applications along with inexpensive, convenient and fast testing of an infinite number of potential sources of gasses or vapors. Potential applications include the monitoring of border crossings for the detection of substances which must be declared or which may not be legally imported, methane monitoring in mining operations and the outdoor monitoring of combustion products, to name just a few. The ready programmability of the apparatus combines the low production cost of uniformity with the convenient

modification for most applications. Cost savings and simple operation enhance distribution and use. The specific IR radiometer and method provided share these advantages and also represent an advancement in system performance. Error producing system noise is reduced and unstable IR background energy is tolerated.

The embodiments described above are intended to be taken in an illustrative and not a limiting sense. Various modifications and changes may be made to the above embodiments by persons skilled in the art without departing from the scope of the present invention as defined in the appended claims.

WHAT IS CLAIMED IS:

1. An infrared radiometer, comprising:

means for collecting infrared energy;

means for filtering the collected energy over a filter bandwidth including filter means for bandpassing only a fractional bandwidth of the filter bandwidth at any one time and means for repeatedly scanning the filter bandwidth with the passed fractional bandwidth;

means for measuring infrared energy passed by the filter means and for producing an output signal in response thereto; and

means for repeatedly nulling the output signal in relation to the repeated scanning of the filter bandwidth.

2. The infrared radiometer of claim 1, further comprising means for synchronizing the means for repeatedly scanning with the means for repeatedly nulling for causing the output signal to be nulled between repeated scans of the filter bandwidth.

3. The infrared radiometer of claim 1, further comprising means for synchronizing the means for repeatedly scanning with the means for repeatedly nulling for causing the output signal to be nulled and the filter bandwidth to be scanned at an identical rate.

4. The infrared radiometer of claim 1, wherein the filter means has a bandpass wavelength which varies over the filter bandwidth and further wherein the fractional bandwidth of the filter means is substantially constant over the filter bandwidth.

5. The infrared radiometer of claim 4, wherein the bandpass wavelength of the filter means varies in accordance with position on the filter means.

6. The infrared radiometer of claim 5, wherein the filter means is circular having a bandpass wavelength which varies with rotational position of the filter means and further wherein the means for filtering further includes means for rotating the filter means in relation to the means for nulling the output signal.

7. The infrared radiometer of claim 4, further comprising means for sampling the output signal a predetermined number of times for each scan of the filter bandwidth which predetermined number is a multiple of the filter bandwidth divided by the fractional bandwidth.

8. The infrared radiometer of claim 7, further comprising computational means for summing output

signal samples from the means for sampling into a multiplicity of filter values each representing a separate wavelength within the filter bandwidth.

9. The infrared radiometer of claim 8, wherein each filter value has a bandwidth substantially equal to the fractional bandwidth of the filter means.

10. The infrared radiometer of claim 9, wherein the computational means includes means for grouping samples for summing for each filter value around the separate wavelength represented by the respective filter value.

11. The infrared radiometer of claim 10, wherein the means for grouping is adapted to include in each filter value those samples representing potential infrared energy passed by the filter means with the wavelength of the respective filter value.

12. A method for measuring infrared energy, comprising the steps of:

collecting infrared energy;

filtering the collected energy over a filter bandwidth including bandpass filtering only a fractional bandwidth of the filter bandwidth at any one time and repeatedly scanning the filter bandwidth with the passed fractional bandwidth;

measuring infrared energy passed by the bandpass filtering producing an output signal in response thereto; and

repeatedly nulling the output signal in relation to the repeated scanning of the filter bandwidth.

13. The method of claim 12, further comprising the step of synchronizing the scanning of the filter bandwidth with the repeated nulling of the output signal for causing the output signal to be nulled between repeated scans of the filter bandwidth.

14. The method of claim 12, wherein the bandpass filtering has a bandpass wavelength which varies over the filter bandwidth and further wherein the fractional bandwidth of the bandpass filtering is substantially constant over the filter bandwidth.

15. The method of claim 14, wherein the bandpass filtering is performed with a circular filter having a bandpass wavelength which varies with rotational position of the filter and further wherein the step of bandpass filtering further includes rotating the filter in relation to the means for nulling the output signal.

16. The method of claim 14, further comprising sampling the output signal a predetermined number of

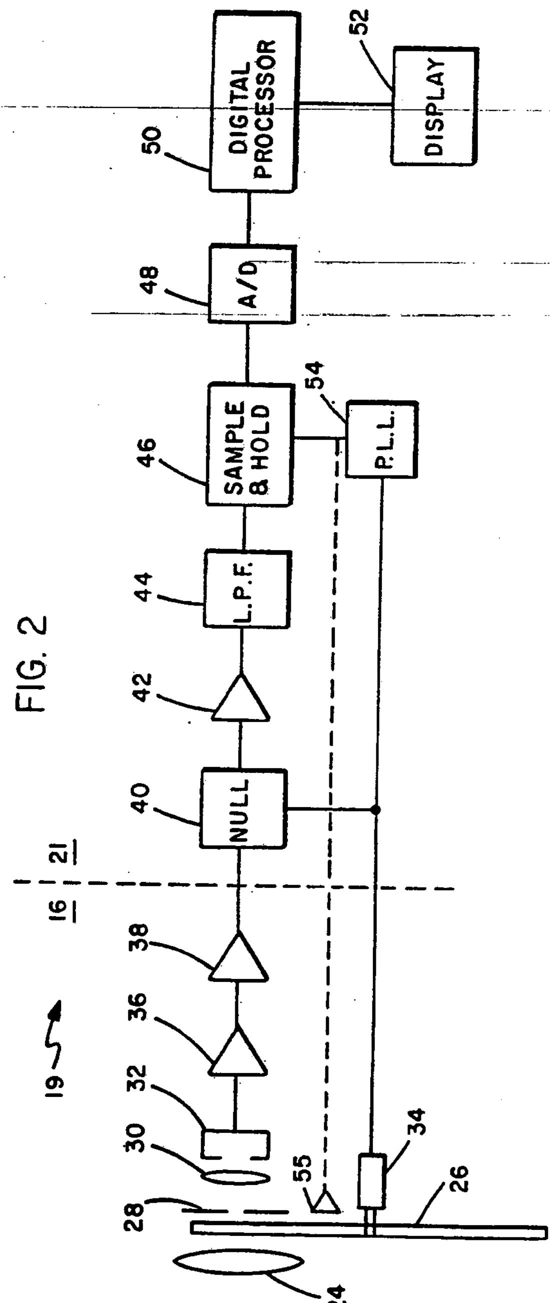
times for each scan of the filter bandwidth which predetermined number is a multiple of the filter bandwidth divided by the fractional bandwidth.

17. The method of claim 16, further comprising summing output signal samples from the sampling step into a multiplicity of filter values each representing a separate wavelength within the filter bandwidth.

18. The method of claim 17, wherein each filter value has a bandwidth substantially equal to the fractional bandwidth used for the bandpass filtering.

19. The method of claim 18, wherein the step of summing includes grouping samples for summing for each filter value around the separate wavelength represented by the respective filter value.

20. The method of claim 19, wherein the step of grouping includes into each filter value those samples representing potential infrared energy passed by the filter means with the wavelength of the respective filter value.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16
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32
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26
34
40
NULL
42
44
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SAMPLE & HOLD
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P.L.L.
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A/D
50
DIGITAL PROCESSOR
52
DISPLAY

FIG. 2

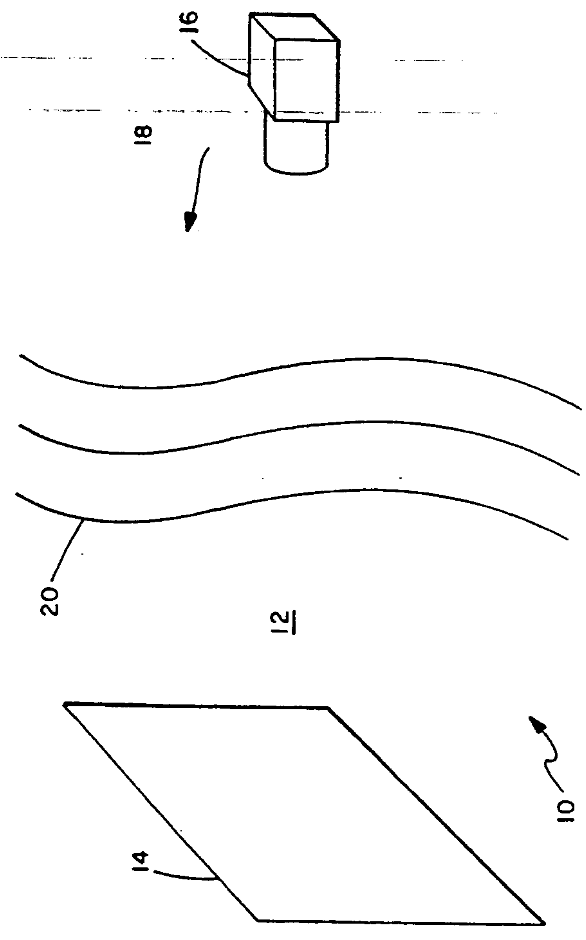
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FIG. 1

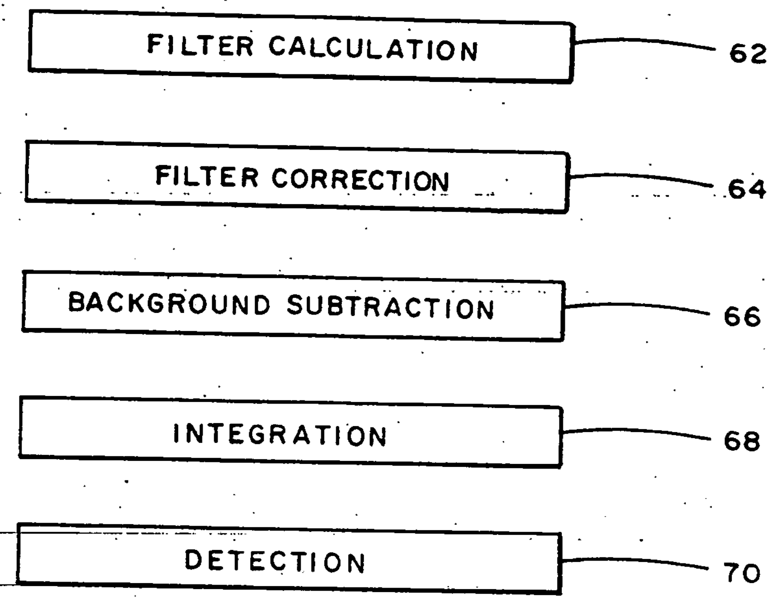
FILTER CALCULATION
62
FILTER CORRECTION
64
BACKGROUND SUBTRACTION
66
INTEGRATION
68
DETECTION
70

FIG. 4

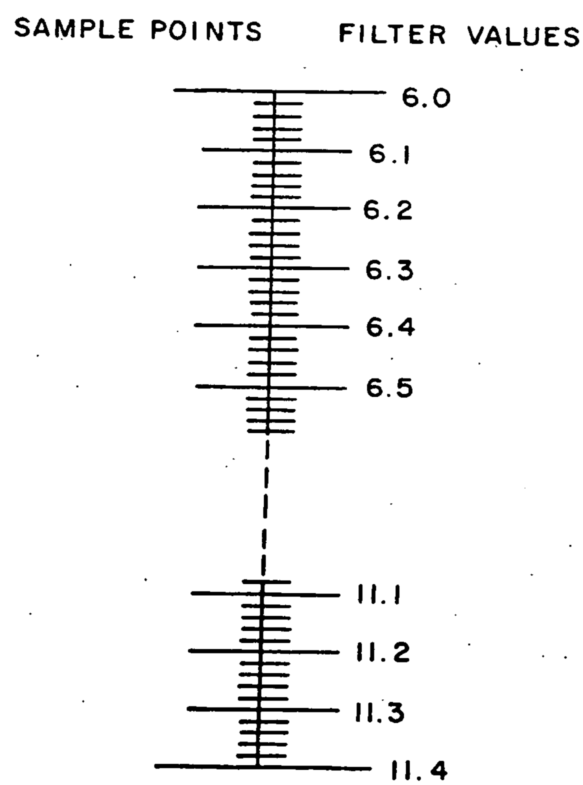
SAMPLE POINTS
FILTER VALUES
6.0
6.1
6.2
6.3
6.4
6.5
11.1
11.2
11.3
11.4

FIG. 3

INTERNATIONAL SEARCH REPORT

PCT/US92/10401

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G01N 21/35
US CL :250/338.5, 339, 351, 343
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 250/338.5, 339, 351, 343

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Please See Extra Sheet.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US,A, 3,663,106 (Minami et al.) 16 May 1972 See Col. 1, line 18, Col. 2, line 39 & Claim 1.	1-20
A	US,A, 3,843,258 (Shupe) 22 October 1974 See the entire document.	1 & 12
Y	US,A, 4,427,306 (Adamson) 24 January 1984 See Col. 3, line 46, Col. 4, line 33, Figure 1.	1-20
Y	US,A, 4,725,733 (Horman) 16 February 1988 See Col. 4, line 62, Col. 5, line 42, Figure 1.	1-20

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

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Date of the actual completion of the international search	Date of mailing of the international search report
13 JANUARY 1993	17 FEB 1993
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. NOT APPLICABLE	Authorized officer for DREW A. DUNN Telephone No. (703) 308-4865

Form PCT/ISA/210 (second sheet)(July 1992)★

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US92/10401

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US,A, 5,075,550 (Miller) 24 December 1991 See Col. 3, line 4-50, Figure 1.	1-20

B. FIELDS SEARCHED

Electronic data bases consulted (Name of data base and where practicable terms used):

APS (Automated Patent System)
S (Infrared or Infra(w)Red) And:
Energy (SA) Bandwidth?
(Nuu or Nulling)(10A)(Output?(SA)Signal).